FJSRL-TR-90-0002

FRANK J. SEILER RESEARCH LABORATORY

AN EXPERIMENTAL INVESTIGATION INTO THE USE OF HOT-FILM ANEMOMETRY TO MEASURE VORTICAL VELOCITY BEHIND A PITCHING WING

AUGUST 1990

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2307-F1-38

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

FJSRL-TR-90-0002

This document was prepared by the Laser Physics Division, Directorate of Lasers and Aerospace Mechanics, Frank J. Seiler Research Laboratory, United States Air Force Academy, CO. The research was conducted under Project Work Unit Number 2307-F1-38, Major C. Bruce Harmon was the Project Scientist in charge of the work.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
Aug 1990

3. REPORT TYPE AND DATES COVERED
Technical Report

4. TITLE AND SUBTITLE
An Experimental Investigation into the use of Hot-Film Anemometry to Measure Vortical Velocity behind a Pitching Wing

5. FUNDING NUMBERS
2307-F1-38

6. AUTHOR(S)
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William Dieterich, Major, USAFR

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
F. J. Seiler Research Laboratory
USAF Academy CO 80840-6528

8. PERFORMING ORGANIZATION REPORT NUMBER
FJSRL-TR-90-0002

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS
hot-film anemometry
vortical velocity
hot-wire anemometers
trailing vortices

15. NUMBER OF PAGES
18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	NONE

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)

An Experimental Investigation into the use of Hot–Film Anemometry to Measure Vortical Velocity behind a Pitching Wing

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Abstract

Much has been done in the instrumentation of airfoils and wings to obtain surface pressure data in support of the characterization of the transient lift augmentation due to unsteady aerodynamic effects. These effects have usually been the result of rapidly rotating wings to high angles of attack or periodic oscillation. Integration of the acquired pressure coefficients leads to the airfoil or wing coefficient of lift. Researchers Walker and Robinson asked for other researchers to explore the use of hot–film anemometry as a confirming technique. In such a role, the anemometry is capable of mapping velocity vs. position, which is used to compute circulation via a line integral. The computed circulation is directly proportional to lift coefficient for a given freestream velocity. This paper describes the investigation into the use of hot–film anemometry, identifies strengths and weaknesses of the approach, and makes specific recommendations regarding its use.

Introduction

Over the last several years, much research has been done in support of unsteady aerodynamics to the extent that it enables the understanding of the underlying physics of supermaneuverability and helicopter dynamics. The Air Force Office of Scientific Research

(AFOSR) has been particularly active and has hosted two national workshops (1983, 1988) at the Frank J. Seiler Research Laboratory at the USAF Academy.

Much of that research has centered on the use of flow visualization and pressure measurement.[1,2] An airfoil or a wing is placed in a low–speed wind tunnel and rotated rapidly to a high angle of attack or is oscillated sinusoidally. The formation and shedding of the transient vortex is observed through photography (smoke wire techniques), and the pressure is recorded at several points on the airfoil or wing surface via flush–mounted transducers and is fed back to a computer for post analysis.

Researchers in this field[1] have identified the need for an independent means to verify the magnitude of the lift augmentation effect as well as a mapping of the flow field several chords downstream. Such a verification would help to validate the results of pressure measurements and help in understanding the physics. Our approach was to use hot–film anemometry as the means of validating previous lift augmentation investigations. A static flow condition was chosen to initially validate the technique. We plan to extend this research to the unsteady case in the coming months.

The methodology used to determine the lift of the static wing was to map the vorticity field of the wingtip vortex. Once the field was known, the circulation of the wingtip vortex could be calculated and from that the lift of the wing could be deduced. This, however, assumes that the wingtip vortex contains all the vorticity that is shed from the wing trailing edge and wingtip. It has been shown that it is necessary to measure the circulation of the wingtip vortex at a distance of at least 1.5 spans downstream of the wing to assure that the vorticity from the wing is rolled up completely in the trailing vortex system.[8] The measurement is then made in the plane perpendicular to the freestream. The wing was placed at an angle of attack that allowed it to operate in the linear range of CL vs α to assure a good match with theory.

LDV (laser doppler velocimetry) and PIDV (particle induced doppler velocimetry) could be used for this purpose, but they are expensive and until recently, unavailable to these researchers. Hot–film anemometry is a well–understood technique and is the basis of the experiments we will describe.

The Equipment

We used the Frank J. Seiler Research Lab (USAF Academy CO) low–speed wind tunnel (LSWT), which contains a 3 ft by 3 ft cross section (7 ft long). The tunnel is controlled to known freestream speed (V_∞) via a manual control knob to a calibrated setting. Data was taken at 10, 20, 30 and 40 ft/s. Reynolds Numbers (based on 6–inch chord) were thus 27000, 54000, 81000, and 108000.

An NACA–0015 wing with 6–inch chord and 33–inch span (actually 16.5–inch semi–span with an end plate) was mounted in the wind tunnel section at a 10–degree angle of attack, extending vertically from the end–plate at the bottom of the tunnel section to the wing tip, which ended up near the center (vertically). Wing aspect ratio was 5.5.

A stepper motor controlled jackscrew traverse was mounted 1.81 spans (60 inches) behind the trailing edge of the wing with a hot–film x–wire probe to measure two dimensions of velocity. The traverse was controlled by an Arrick dual stepper motor control system via MD–2 software installed on a Zenith 248 computer. The stepper motor was commanded to position the probe on the traverse to each position in a grid of x–y coordinates across the section cross–section. Grid spacing was 1/2 inch.

The hot–film probe was oriented in the tunnel at 45 degrees from the freestream, in the horizontal plane. This was to capture all the freestream velocity on channel 2 and all the vortical velocity on channel 1. This technique was required in this instance, but none of the literature discussed the taking of measurements outside the cone of validity, which is

defined as plus or minus 20 degrees from the bisector of the two x probe cylinders. We were well outside that cone of validity and had to generate our own calibration technique to account for the hot–film cooling due to flow parallel with the hot–film cylinder.

While the traverse maintained position, the hot–film voltage was read manually and recorded. Two channels of data were taken into account for velocity in each direction associated with the x–wire probe. The TSI Inc hot–film anemometry system was used.

The data was entered manually into the Masscomp MC–5500. Data analysis was performed on the Masscomp and on a VAX, using SP40 and Disspla graphics as needed.

Discussion

To begin the experiment, we calibrated the two channels of a known good probe. This probe (#34032) proved reliable throughout the experiment. We obtained spurious results with the only other x–probe available to us and discarded it. According to the TSI documentation, each channel can be expected to adhere to King's Law whereby the channel voltage squared is a linear relationship with respect to the square root of velocity.

$$e^2 = m * \mathrm{sqrt}\,(v) + b$$

where e is channel voltage measured with cylinder normal to flow

v is freestream velocity (V_∞)

m is slope

b is y–intercept, the value of e^2 when $v=0$.

The calibration thus requires one to take two or more known freestream velocities and record the maximum e each channel "sees" at each velocity. The result is a calibration for each channel that allows one to determine v for a measured e. See figure 1 for such a calibration. Previous researchers at the Seiler Lab had calibrated the tunnel velocity.

Much to our surprise, this slope and intercept varied channel–to–channel, and day–to–day. We experienced about a five percent variation in these parameters overall.

Another problem was that King's Law broke down altogether at 1–2 ft/s. This led to a poor curve fit below 2 ft/s. The results in that regime are thus suspect. Had this regime been more important, we would have done a piecewise curve fit to account for it. However, that flow regime turns out to be of little consequence. For example, at V_∞=30 ft/s, the circulation is best calculated (as we discovered) around contours of 4–7 ft/s vortical velocity.

We also found a high sensitivity to operating resistance of the TSI equipment. This value is determined during the calibration of the anemometry on the day of the experiment. If the wrong value is used, the results can be very far from correct. See figure 2. These sensitivities taught us the extreme importance of attention to detail during calibration and measurement.

As was mentioned above, the probe was oriented in the tunnel such that channel 1 would detect vortical velocity as a velocity normal to the wire and freestream velocity would be parallel to the wire's orientation in the tunnel. Channel 2, which was oriented perpendicular to the freestream flow in the tunnel, also was sensitive to both freestream and vortical velocity components. For this investigation however, Channel 2 data was not needed. Because the vortical and freestream components of velocity had combined effects on the hot–wire measurement, a correction needed to be made. This correction was made with the previously determined yaw factor and the resulting data was input to Disspla software to produce contours of constant V_N. The contours were used to manually calculate circulation via the line integral of $\oint \bar{V}_N \cdot d\bar{s}$. This was approximated by determining the average distance from the center of the vortex to the relevant contour. This average radius was multiplied by two π times V_N to get circulation. The CL is given by twice the circulation divided by the quantity V_∞ times the chord.

Theory predicts that the CL for the NACA–0015 at Reynolds Number of 81000, V_∞=30 ft/s, AR=5.5, τ=0.16, and α=10 degrees is about .61. The resulting theoretical circulation is 4.575 ft^2/s. For other V_∞, the CL remains essentially the same while circulation is proportional to V_∞. In the final analysis, our measured values of circulation were 25–30 percent short of the theoretical values.

The location of the center of the vortex core was the objective of one experiment. We found it where others had predicted it: slightly down and inward from the wingtip. Its exact location corresponded to Hoerner's rule, where the distance between the two vortex cores is π times span divided by 4. However, our data also suggests that the vortex center meanders, much as others had observed.[3] This was problematic in that the rate of meandering (about one second period) was faster than our data collection, so that the result was an imprecise center location. In addition, it had the effect of washing out the effect of the vortex, not allowing it to maintain high V_N at a particular point in the flow. This error was predicted by Corsiglia[3] to be on the order of a few centimeters. This introduced an error in the final circulation calculation that cannot be precisely known.

Although the calculations produced relatively low values vs. the predicted, the vortex meandering seems to explain a great deal of this shortfall. The plotted contours are shown in figure 3 and match the pattern expected. The vortex meandering is clearly visible on this figure.

Sensitivity

It is significant to note that we first approached yaw coefficient k as a constant since TSI documentation characterized it as such. However, since the data was collected in a domain outside the cone of validity for the TSI model, we decided to investigate further and found k to be a strong function of V_∞ and V_N/V_∞.

First, we found that the use of yaw coefficient k as described by the manufacturer of the hot–film equipment and application notes was inappropriate outside the cone of validity previously described. The manufacturer predicted a value of .2–.3. We found that the number was more like .34 at the test velocities. The yaw coefficient relates how sensitive the hot–film cylinder is to parallel flow. An infinitely long cylinder would have a value of k of zero. The relationship is

$$q^2 = V_N^2 + k^2 * V_T^2$$

where q is the effective velocity sensed by electronics

V_N is velocity normal to cylinder

V_T is velocity tangent to cylinder

k is yaw coefficient — nearly constant

The orientation that we required to use, put channel 1 in such a position that the tangent flow was always several times the normal flow. V_N rarely reached 40% of V_T.

The TSI recommended technique is to use q in the King's Law formula in place of v and then to use a constant yaw coefficient k to relate back to V_N. We found that k was a strong function of V_∞ and V_N/V_∞. So strong was this function that to treat k as constant in either domain would skew the results wildly. The results of these calibrations are shown in figures 4 and 5. Yaw coefficient k vs V_∞ is fit as an exponential decay. Yaw coefficient vs V_N/V_∞ is fit as a parabola with open side down. As can be seen in figure 4, these calibrations vary from day to day but are essentially the same shape. One can see from the shape of figure 5 that one should not use data outside of $V_N/V_\infty <= 0.3$, since it is hard to maintain a curve fit over a larger range. That should not be too restrictive in that that allows contours up to V_N=9 ft/s with V_∞=30. Such a contour is too close to the vortex center to be reliable in the context of a meandering center. Further, we found the instrumentation unreliable at wind tunnel speeds above 35 ft/s, perhaps a local problem.

Conclusion

After extensive post-acquisition calibration, we concluded that the technique is highly suspect in this regime due to the need to orient the probe outside of published parameters. Still, the calibrations made led to a result and a reasonable contour map and a reasonable total circulation calculation. This final calculation is about 25–30% low. However, it is very important to note that the vortex did clearly meander as predicted by other researchers. This meandering can be seen in the contour map shown on figure 3. One would expect that this meandering (on the order of 1 sec period over about 1–2 inches travel) would wash out the vortex effect as seen by an averaging technique whose time interval is several meander periods. Thus, the low circulation should be expected. We do not have that completely quantified.

Recommendation

We think this technique can be used as a back-up to the measurements taken via pressure transducers, LDV, or PIDV. The technique provides a relatively quick result that lacks the accuracy of other techniques but which can be confirming. The general nature of the lengthy calibration process is understood but must be repeated with extreme attention to detail. New curve fits will need to be made, based on the behavior of the instrumentation near the data of the "unsteady" experiment.

The vortex meandering clearly compromises the results. One cannot count on the data being accurate if one takes temporal data at a point and then moves the probe to a new point to repeat the motion and take the data again expecting to correlate the results with respect to time after the experiment. The meandering will preclude that. Thus, it would seem that a hard look should be taken at PIDV and other techniques that capture the whole flow field at once.

Having said that, it is clear that the results taken in the unsteady case can be expected to be smaller than the real answer by some amount, perhaps by the same amount as in the experiment described herein. Thus, we recommend that an unsteady experiment be run wherein the results are clearly known. Such an experiment should confirm or deny its viability as a backup measurement technique in support of unsteady aerodynamics.

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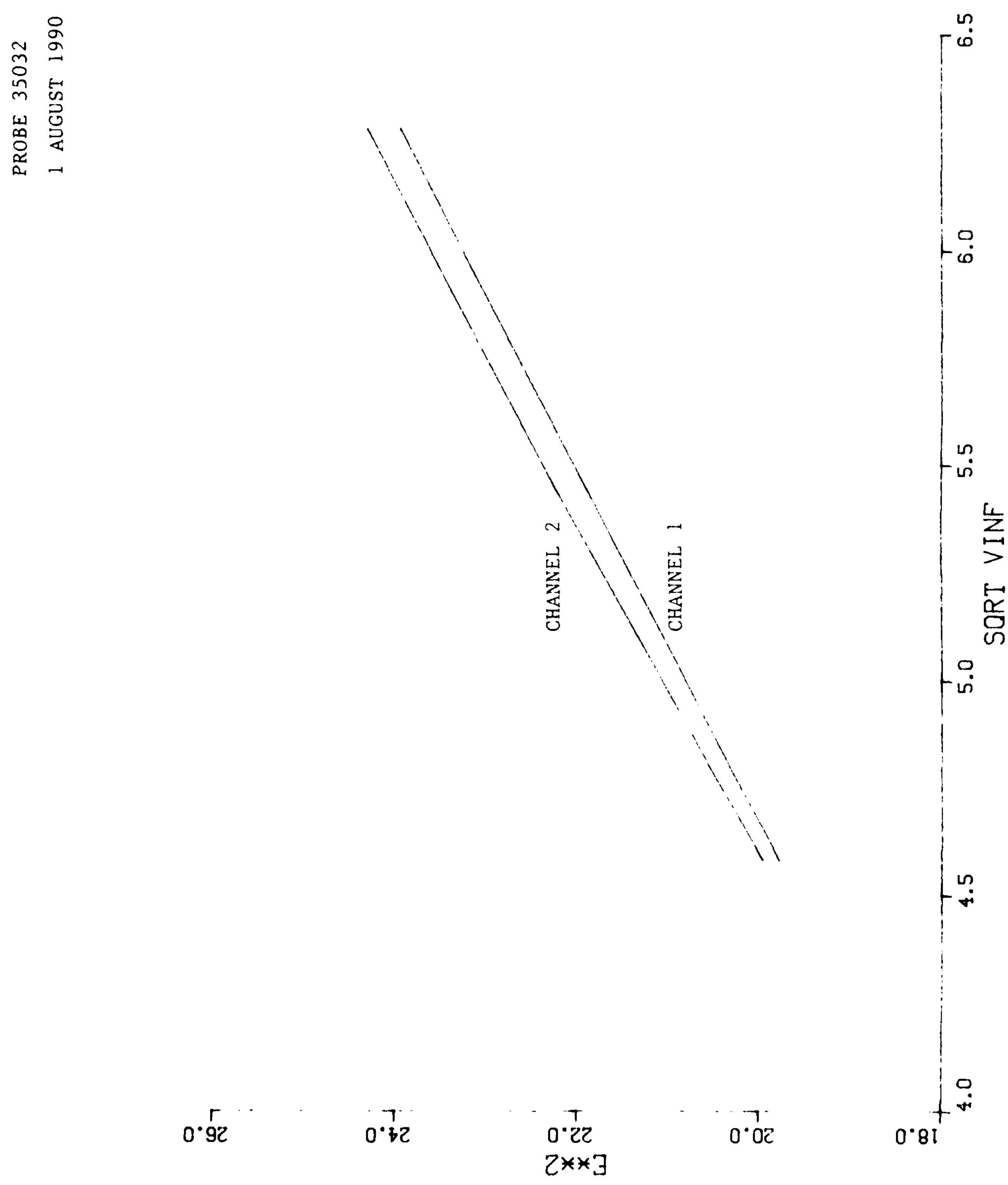


PROBE 35032
1 AUGUST 1990
CHANNEL 2
CHANNEL 1
SQRT VINF
E**2
4.0
4.5
5.0
5.5
6.0
6.5
18.0
20.0
22.0
24.0
26.0

FIGURE 1

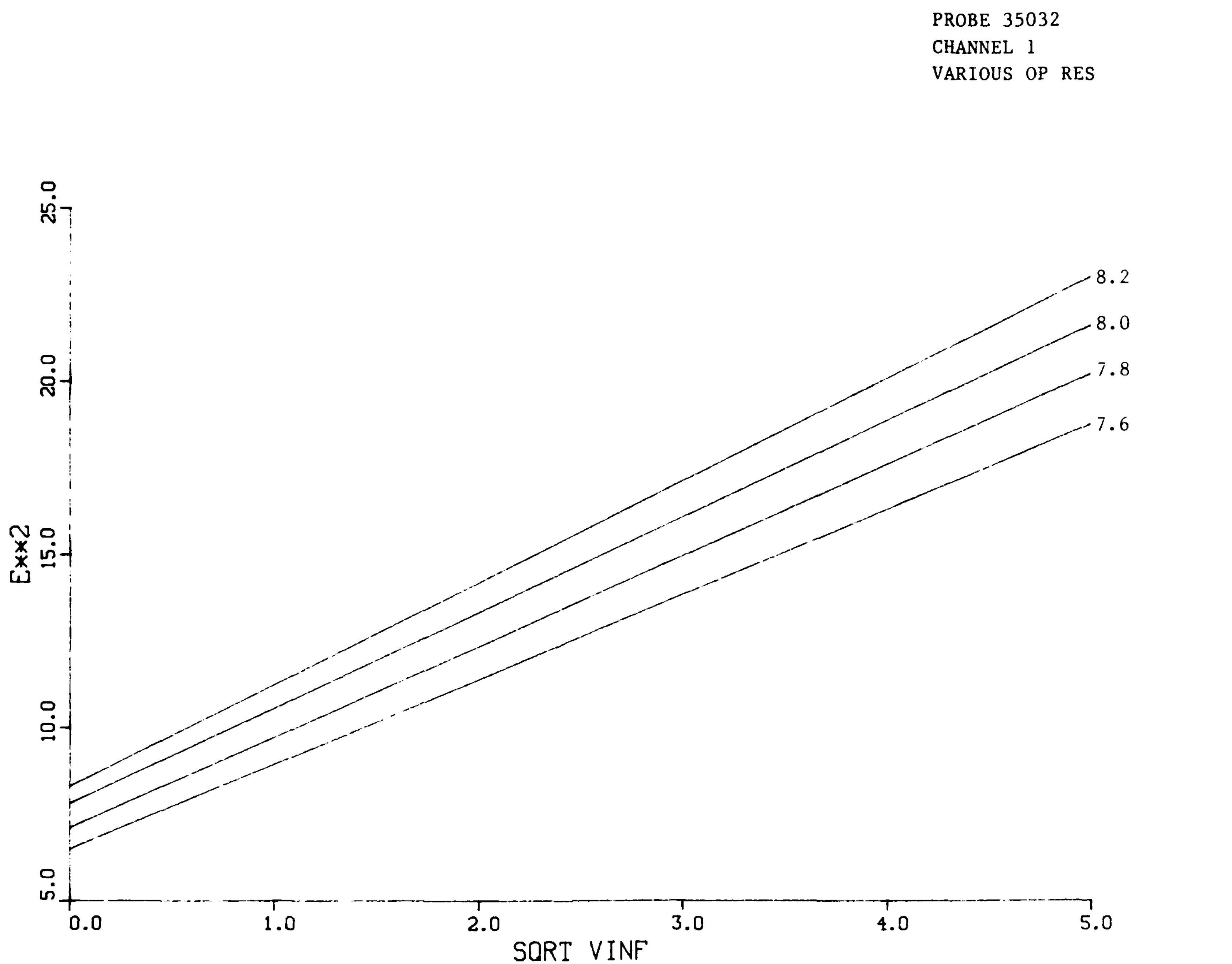

PROBE 35032
CHANNEL 1
VARIOUS OP RES
25.0
20.0
15.0
10.0
5.0
E**2
8.2
8.0
7.8
7.6
0.0
1.0
2.0
3.0
4.0
5.0
SQRT VINF

FIGURE 2

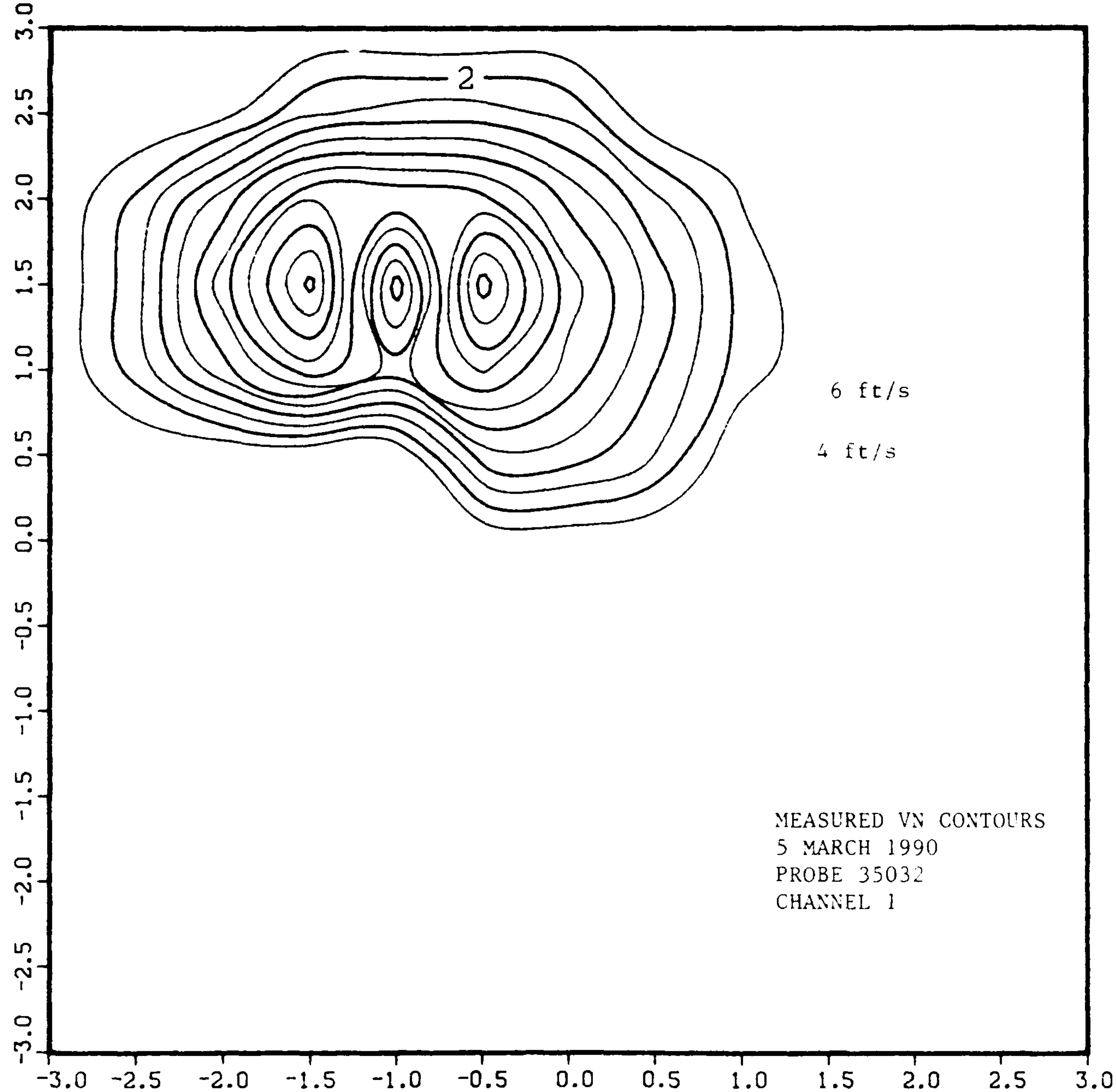

2
6 ft/s
4 ft/s
MEASURED VN CONTOURS
5 MARCH 1990
PROBE 35032
CHANNEL 1
-3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0
-3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0

FIGURE 3

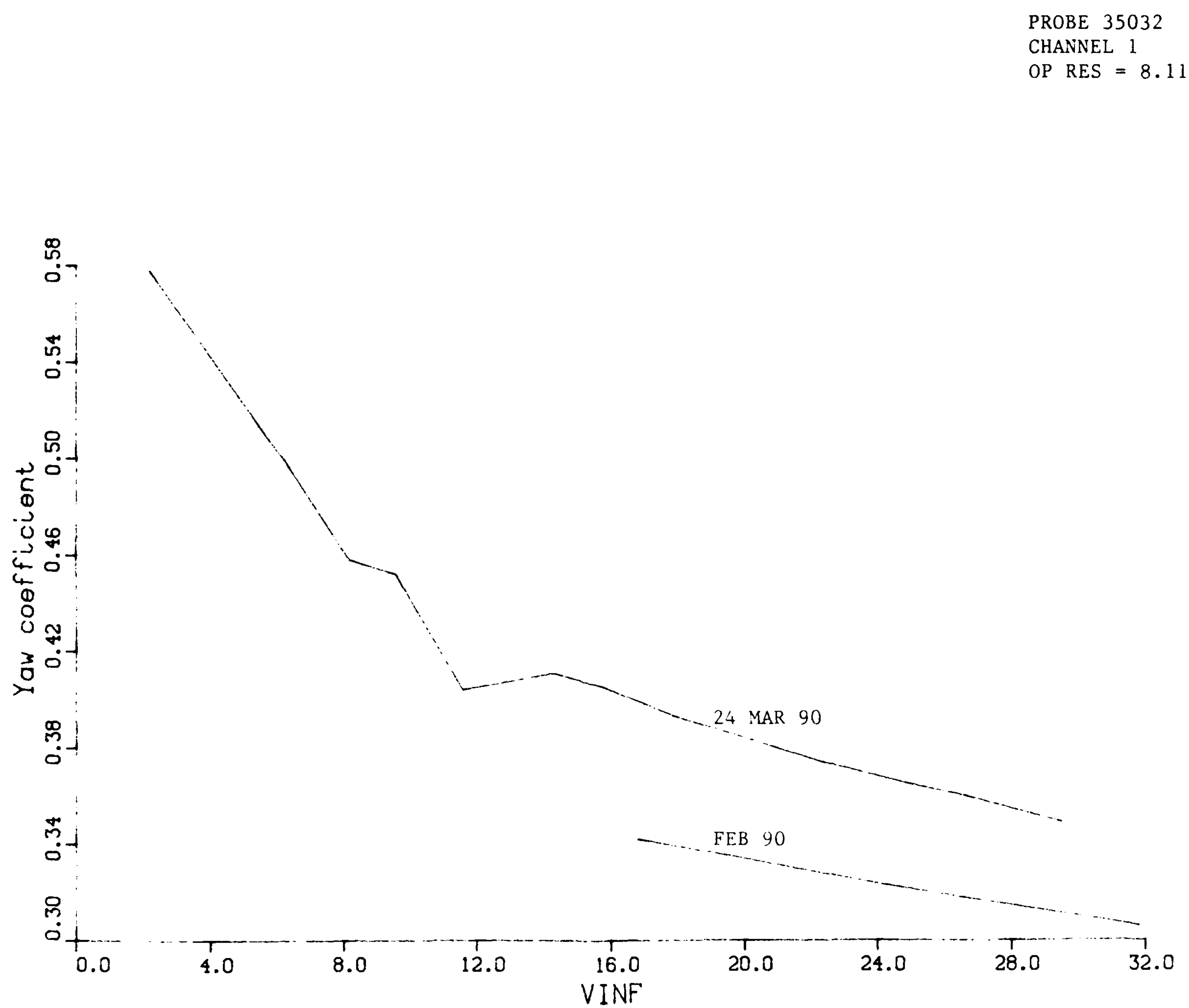
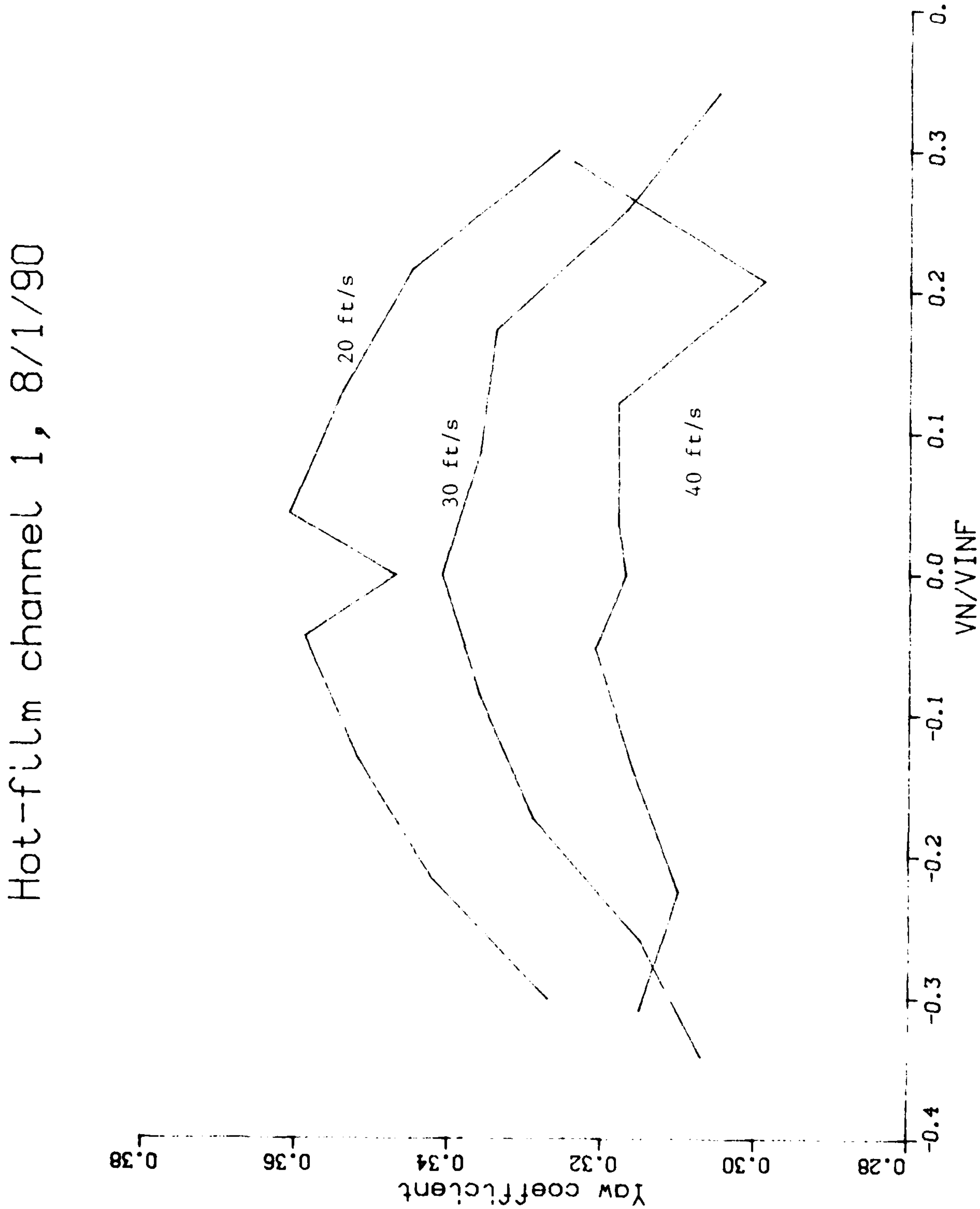

PROBE 35032
CHANNEL 1
OP RES = 8.11
Yaw coefficient
0.58
0.54
0.50
0.46
0.42
0.38
0.34
0.30
0.0
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
VINF
24 MAR 90
FEB 90

FIGURE 4



Hot-film channel 1, 8/1/90
20 ft/s
30 ft/s
40 ft/s
Yaw coefficient
0.28
0.30
0.32
0.34
0.36
0.38
VN/VINF
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4

FIGURE 5